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Department of Physics and Astronomy
THE UNIVERSITY OF IOWA

Iowa City, Iowa 52242

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Electrical Interference to Satellite Subsystems Resulting from Spacecraft Charging

by

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INTRODUCTION

Advanced electronics technology has been extensively used in synchronous orbiting satellites for both research and practical applications such as weather forecasting and communications. It is necessary that such spacecraft operate reliably in the space environment.

Recently, an aspect of the environment at synchronous altitude that can lead to serious operational problems has been identified. DeForest has reported that ATS-5 and ATS-6 charge to voltages as great as several thousand volts during magnetospheric substorms [1972, 1974]. Satellite charging is caused by charged-particle currents from the surrounding plasma collected by the satellite (thermal electrons and ions) and charged-particle currents emitted by the satellite to the surrounding plasma (photoelectrons, secondary electrons, and backscattered electrons).

It is believed that satellite surfaces charge to the highest voltages during magnetospheric substorms. The magnitude of the voltage to which a satellite charges is roughly equal to the thermal energy of the dominant current constituent. During substorms, the dominant constituent is energetic plasma sheet electrons that are injected from the geomagnetic tail to synchronous orbit altitudes [DeForest and McIlwain, 1971]. These electrons have thermal energies of several

thousand electron volts, and, accordingly, satellite surfaces may charge negatively to voltages as great as ten thousand volts.

If a satellite has dielectric surfaces, those surfaces can charge to voltages that are large with respect to the frame of the satellite. If this voltage exceeds the breakdown voltage of the dielectric, an electrical discharge occurs.

It has been suggested that electromagnetic fields radiated from discharges, or direct-current surges from the discharges, may cause a spacecraft to operate with unexpected behavior that may be difficult to anticipate from ground testing [Fredricks and Scarf, 1972; Cauffman, 1973a; Rosen, 1975]. Such anomalies, believed to be correlated with periods of enhanced substorm activity, have been observed on numerous spacecraft from several different missions flown at synchronous altitudes. One satellite failure was associated with unusual magnetospheric activity at synchronous altitudes [Rosen, 1975 and Wynne, 1975]. In addition, ground-based laboratory tests have shown that discharges cause physical damage to thermal-control materials that are charged to voltages sufficient to generate electrical breakdowns [Nanevicz et al., 1974]. Satellite charging can also cause the reattraction of ionized contaminants that are emitted from a spacecraft [Cauffman, 1973b]. As a consequence, satellite charging may contribute to deterioration of dielectric surfaces used for passive thermal control causing parts of the spacecraft to operate at undesirable temperatures [Shaw et al., 1976].

Recently, an experiment was flown on a synchronous orbiter to detect the presence of satellite charging, to detect the occurrence of electrical discharges caused by differential charging of the dielectric surfaces, and to detect coincidences between electrical discharges and the anomalous responses of several other spacecraft subsystems, which had been observed on previous missions of the same type of spacecraft. An example of data collected from this experiment is shown in Figure 1.

The interpretation of data from this experiment has been discussed in detail elsewhere; therefore, the major findings of this investigation will only be summarized briefly in this report [Shaw _et al._, 1976]. Data collected by the current probe, shown in Figure 1, shows a spacecraft charging event (presumably caused by the injection of energetic plasma to synchronous altitudes during a magnetospheric substorm) beginning at approximately 23.7 hours local time when the spacecraft is eclipsed by the earth. The charging event is indicated by a small decrease in the total current density (measured across the probe area) during eclipse. Following eclipse the current density is decreased significantly from the value of 10 to 20 μamps m^{-2} typical of photoelectric emission from the probe usually observed at these orbital locations. This indicates that the spacecraft is immersed in energetic plasma electrons that can cause charging of spacecraft dielectric surfaces.

Near the beginning of the charging event the pulse counter begins to detect electrical discharges occurring on these dielectric

surfaces as previously described by Cauffman and Shaw [1975]. Rates of four to ten per minute are observed during this event, and an anomalous response of a detector is also observed on another subsystem during this event. Twenty-five anomalous detector responses were observed on this pass, and each of the twenty-five responses was observed coincidently with the detection of a discharge by the pulse counter experiment. (The pulse counter is sampled once per second and the detector is sampled more rapidly so that this coincidence is definitely not caused by overlapping data storage in the spacecraft data system.)

The principal findings from analysis of data collected from this experiment were that discharges occur at rates averaging about 20 per hour, and that two different types of anomalous behavior of the spacecraft's electronics subsystems do occur coincidently with discharges detected by the instrumentation and are, therefore, presumed to be caused by these discharges [Shaw et al., 1976]. These anomalies occur infrequently in orbit; hence, it takes a specific discharge at a specific location on the spacecraft to generate such an anomaly because many discharges occur for which no anomalies are observed.

This paper reports some results of a study carried out to explain how the energy from electrical discharges generated by satellite charging couples into spacecraft electronics systems. Particular emphasis was placed on developing an understanding of the specific types of coupling mechanisms causing the anomalies on the type of spacecraft on

which the charging experiment was flown, for example, the anomalous detector responses shown in Figure 1. This paper reviews briefly the relatively simple coupling mechanism that was proposed to explain how discharges couple energy to this detector located well within the structure of the spacecraft. The following sections describe this mechanism and the engineering tests that were conducted to verify it.

DESCRIPTION OF ANOMALOUS DETECTOR RESPONSE

One type of orbital anomaly investigated in this study is the anomalous response of a detector located well within the structure of the spacecraft. Figure 2 schematically shows the configuration of this detector, the spacecraft sturcture, and the associated signal processing electronics.

The detector is mounted on a structural member, the mountings of which are electrically isolated from the frame of the spacecraft for thermal purposes. This structural member passes through the spacecraft skin and is attached to a passive thermal radiator that is covered with dielectric surfaces. The detector is mounted on this structural member inside the spacecraft, and it is connected to a preamplifier through a long coaxial cable as shown schematically in Figure 2. The structural member is grounded to the frame of the spacecraft through the shield of the coaxial cable.

This subsystem has been observed to have responses in orbit that cannot be due to a normal stimulus of the detector, because the characteristics of the response differ significantly from the response to its usual stimulus. These responses are, therefore, easily identified and ignored by ground processing equipment. These anomalous responses have been observed to occur in coincidence with discharges observed by the satellite-charging experiment flown on this spacecraft [Shaw <u>et</u> <u>al.</u>, 1976] (see also Figure 1 of this paper).

When an anomalous response is observed, the preamplifier is observed to have an output waveform similar to that shown schematically in the lower panel of Figure 2. The preamplifier is observed to "ring" near the center frequency of its band pass and the resultant oscillation is damped as shown in Figure 2. The anomalous response is characterized by the ratio between the first and second peaks in this oscillation, P_1/P_2, and the time interval, ΔT, between the times at which these peaks occurred.

The anomalous responses fall into two distinct groups, or types, based on their observed characteristics as shown in Figure 3. Responses that we call Type P anomalies have values of P_1/P_2 equal to about 1.15 and ΔT equal to about 3.75 data frames. (One data frame is equal to one complete sample of the detector.) The second category of anomalous responses, which we call Type N anomalies, have values of P_1/P_2 equal to 5.90 and ΔT equal to 5.75 data frames. (The separation between the three apparent subgroups of Type N responses shown in Figure 3 is caused by the digitizing step size in the data processing equipment.)

Any mechanism that uses electrical discharges as an energy source to generate these anomalies must couple sufficient energy into the electronics to account for the amplitude, P_1, and also for the spectral characteristics, P_1/P_2 and ΔT, that are observed in orbit. This study has identified such a mechanism.

Figure 2 shows how a Type N anomaly is generated. An electrical discharge can occur from the charged surface of the passive thermal radiator to the supporting structural member if the voltage between the

dielectric surface and the metallic support exceeds the breakdown voltage of the dielectric. The discharge represents an injection of electrons to the structural member, and these electrons constitute a current that flows through the cable shield, through the ground clamp at the preamplifier, and into the spacecraft frame. (The assembly is electrically insulated from the frame, except through the cable shield clamped to the signal processing electronics housing.)

Because the cable shield and the connection at the ground clamp has a finite dc resistance, a voltage pulse exists on the supporting structure and the cable shield. This voltage pulse is coupled into the detector signal lead because of the capacitance of the signal lead to the cable shield. Thus, a voltage pulse exists at the preamplifier input and the resulting output is observed as an anomalous response of the subsystem.

This mechanism accounts for all observed features of the anomalous detector responses. Also, the characteristics of both Type N and Type P anomalies can be explained by this generating mechanism as shown in Figure 4. Voltage pulses of both positive and negative polarity can be produced at the preamplifier input for discharges occurring either on or next to the thermal radiator. A discharge occurring on the assembly produces a negative voltage pulse at the preamplifier, and a discharge occurring next to the radiator produces a positive voltage pulse because of ground return currents that are induced by the discharge. (See Figure 4.) For this case, the radiator acts like a short-range antenna, and the coupling strength should

decrease roughly as the inverse cube of the distance of the discharge from the assembly [Cauffman and Shaw, 1975]. This behavior is observed in orbit. The Type N responses have amplitudes that are constant to within a factor of 2 or 3. The amplitudes of Type P anomalies vary several orders of magnitude, however, because of the variation in coupling strength with the location of the discharge.

An engineering simulation was carried out to experimentally determine the response of this system to the currents injected by the discharges. The purpose of this simulation was to compare the responses generated in the test with the anomalous orbital responses to check the validity of this generation mechanism. The remainder of this paper consists of a description of these tests and the results obtained.

ENGINEERING TESTS

Because the bandpass of the preamplifiers is at low frequencies an equivalent circuit of the configuration shown in Figure 2 can be drawn as shown in the upper half of Figure 5. This circuit contains the essential parameters that determine the amplitude of the signal that is coupled into the preamplifier by the discharge current injected from the dielectric surfaces to the supporting structural member.

The discharge current was represented by a double exponential current source with a near zero rise time and a long decay time. Laboratory experiments with several types of dielectric materials suggest that the rise times of these currents are probably near 10^{-7} seconds and that the decay times may vary from 10^{-7} seconds to 10^{-4} seconds depending on the type of materials and the physical configuration used [Cauffman, 1973c]. Some theoretical considerations suggest that rise times of vacuum breakdowns may be as short as 10^{-8} seconds [Germain and Rohrbach, 1968].

The other factors influencing the amplitude of the signal coupled into the preamplifier are the resistance between the structural member and the spacecraft frame (labeled R_{SH} in Figure 5), the cable capacitance (C_{CABLE}), and the parallel combination of the detector resistance (R_D) and the preamplifier input resistance (R_{IN}).

This equivalent circuit was modeled in the laboratory as shown in the lower half of Figure 5. An exponentially decaying current source was generated by a differentiating the output of a pulse generator with a variable pulse rise time as short as 10^{-8} seconds. To simulate the cable capacity, a cable of the type and length used on the spacecraft was used to couple the signal to a preamplifier. A resistor, R_D, was used to simulate the detector resistance.

Several pulse decay times were selected, and a comparison was made between the laboratory model and the spacecraft configuration on a development test model of the spacecraft. The results of this comparison indicated that the model was an accurate representation of the system response to within about twenty percent. This accuracy was judged to be adequate for the purposes of this test.

The results of the pulse injection tests are summarized in Figure 6. The left hand panels of Figure 6 show the amplitude ratio P_1/P_2 and time delay ΔT for a negative pulse with five different pulse decay times between 10^{-5} seconds and 10^{-2} seconds. The horizontal straight lines show the average value of P_1/P_2 and ΔT for the Type N anomaly.

Two features of Figure 6 are worth noting. First, the test results are in agreement with the values of P_1/P_2 and ΔT recorded on orbit for the Type N anomaly. (The precision of the test measurements is denoted by the vertical error bars.) Second, the system has the same response for any pulse shorter than about 1 millisecond. This occurs because the pulse is short enough so that its frequency content is nearly flat in the bandpass of the preamplifier filter. The response

observed for this pulse (or any shorter pulse) is the impulse response of the system, and it is independent of the excact shape of the pulse.

To experimentally check this a square pulse 10 microseconds in width was used as an injected current to the simulated detector assembly. The response to the square pulse, labeled "impulse" response in Figure 6, was indistinguishable from those of the shorter exponentially decaying current pulses. Decreasing the width of the square pulse and increasing the amplitude by a factor of ten generated the same response as the 10-microsecond-wide pulse.

The right hand panels of Figure 6 show the test results for P_1/P_2 and ΔT for a positive pulse. These results are also in agreement with the corresponding values for P_1/P_2 and ΔT for the Type P anomalies.

These tests have shown that the generating mechanism described herein produces the spectral characteristics observed in orbit for these anomalies. In addition, this mechanism must predict reasonable values for the intensity of the preamplifier response.

The intensity cannot be calculated exactly because there is an important parameter that is not known. The total amount of charge participating in the discharges in flight has not been measured. Knowledge of the total charge is necessary to calculate the peak voltage of the preamplifier response. The observed peak voltage can be used, however, to calculate the total charge required to produce the anomalous response. This value can then be compared with other measurements made in laboratory experiments.

Table 1 lists typical discharge parameters that have been measured in laboratory experiments with similar dielectric surfaces at the Stanford Research Institute [R. C. Adamo, private communication, 1974] and the parameters required to produce the anomalous detector responses. Approximately 6 μcoul of charge must participate in a discharge to produce the values of P_1 for these anomalous responses.

This value is reasonable when compared with laboratory measurements, as shown in Table 1. It is possible that slightly greater amounts of charge participate in a typical discharge in the orbital environment. This may be caused by contaminant films that could be present on the dielectric surfaces. Such films might increase the charge mobility parallel to the surface, resulting in slightly larger discharges. In any case, the amount of charge needed to cause the anomalous responses is in agreement with that typically measured in laboratory experiments.

SUMMARY

A physically reasonable mechanism for explaining the coupling between one type of spacecraft electronics subsystem and electrical discharges has been presented. A laboratory simulation of the coupling to the signal processing electronics has shown quantitative agreement between the test results and the anomalous detector responses that have been observed in orbit. The results of this study and experimental flight data collected by a satellite-charging experiment flown on this spacecraft confirm that these anomalies are likely generated by direct current surges from arc discharges.

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TABLE 1

COMPARISON OF CALCULATED DISCHARGE PARAMETERS
WITH LABORATORY MEASUREMENTS

Characteristic	Probable Value	Determination
Total Charge	~ 6 μcoul	Coupling analysis
	0.2 - 2.0 μcoul	SRI laboratory experiments
Pulse Length	Less than ~ 1 ms	Comparison of pulse injection tests and orbital data
	< 1 μs - 40 μs	SRI laboratory experiments

REFERENCES

Cauffman, D. P., Correlation of Strobe Anomalies with Geophysical Parameters, ATM-74 (4409-04)-3, The Aerospace Corporation, El Segundo, CA, 1973a.

Cauffman, D. P., Ionization and Attraction of Neutral Molecules to a Charged Spacecraft, TR-0074 (9260-09)-1, The Aerospace Corporation, El Segundo, CA, 1973b.

Cauffman, D. P., Recommendations Concerning Spacecraft Charging in the Magnetosphere, Report No. SPL-33302, The Aerospace Corporation, El Segundo, CA, 1973c.

Cauffman, D. P. and R. R. Shaw, "Transient Currents Generated by Electrical Discharges," Space Science Instrumentation, 1, 125, 1975.

DeForest, S. E. and C. E. McIlwain, "Plasma Clouds in the Magnetosphere," J. Geophys. Res., 76, 3587, 1971.

DeForest, S. E., "Spacecraft Charging at Synchronous Orbit," J. Geophys. Res., 77, 651, 1972.

DeForest, S. E., Correlation of Plasma Measurements on ATS-5 and ATS-6, Special Session on Initial Scientific Results from ATS-6 presented at the Fall Annual Meetings of the American Geophysical Union, San Francisco, CA, 1974.

Fredricks, R. W. and F. L. Scarf, "Observations of Spacecraft Charging Effects in Energetic Plasma Regions," Photon and Particle Interactions with Surfaces in Space, D. Reidel Publishing Co., Dordrecht, Holland, 277, 1972.

Germain, C. and F. Rohrbach, "High Voltage Breakdown in Vacuum," Vacuum, 18, 371, 1968.

Nanevicz, J. E., R. C. Adamo, and W. E. Scharfman, Satellite Lifetime Monitoring, SRI Project 2611, Stanford Research Institute, Menlo Park, CA, 1974.

Rosen, A., Spacecraft Charging: Environment Induced Anomalies, presented at the AIAA 13th Aerospace Sciences Meeting, Pasadena, CA, 1975.

Shaw, R. R., J. E. Nanevicz, and R. C. Adamo, "Observations of Electrical Discharges Caused by Differential Satellite Charging," Spacecraft Charging by Magnetospheric Plasmas, Progress in Astronautics and Aeronautics, Vol. 47, American Institute of Aeronautics and Astronautics, New York, NY, 1976.

Wynne, H., Operational Experience with Satellite Anomalies, presented at the AIAA 13th Annual Aerospace Sciences Meeting, Pasadena, CA, 1975.

FIGURE CAPTIONS

Figure 1 Satellite-charging experiment data collected during a period with twenty-five anomalous responses of a detector on another spacecraft subsystem. Each of these anomalous responses occurred coincidently with a discharge observed by the charging experiment.

Figure 2 Mechanism for generating anomalous detector responses from discharge generated currents.

Figure 3 Anomalous detector responses occur in two distinct groups, which we call Type N and Type P. Apparent separation of Type N anomalies is caused by digitizing step size in signal processing electronics.

Figure 4 Negative voltage pulses (causing Type N anomalies) are caused by direct injection of electrons to the metallic support for the passive thermal radiator. Type P anomalies are caused by positive voltages resulting from ground return currents caused by discharges occurring near the radiator assembly. All external surfaces shown are dielectric surfaces.

Figure 5 Equivalent circuit model and laboratory test configuration for modeling the detector subsystem response to discharges.

Figure 6 Test responses for negative and positive voltage pulses are in agreement with the orbital characteristics of Type N and Type P anomalies for discharges with decay times less than about 1 msec.

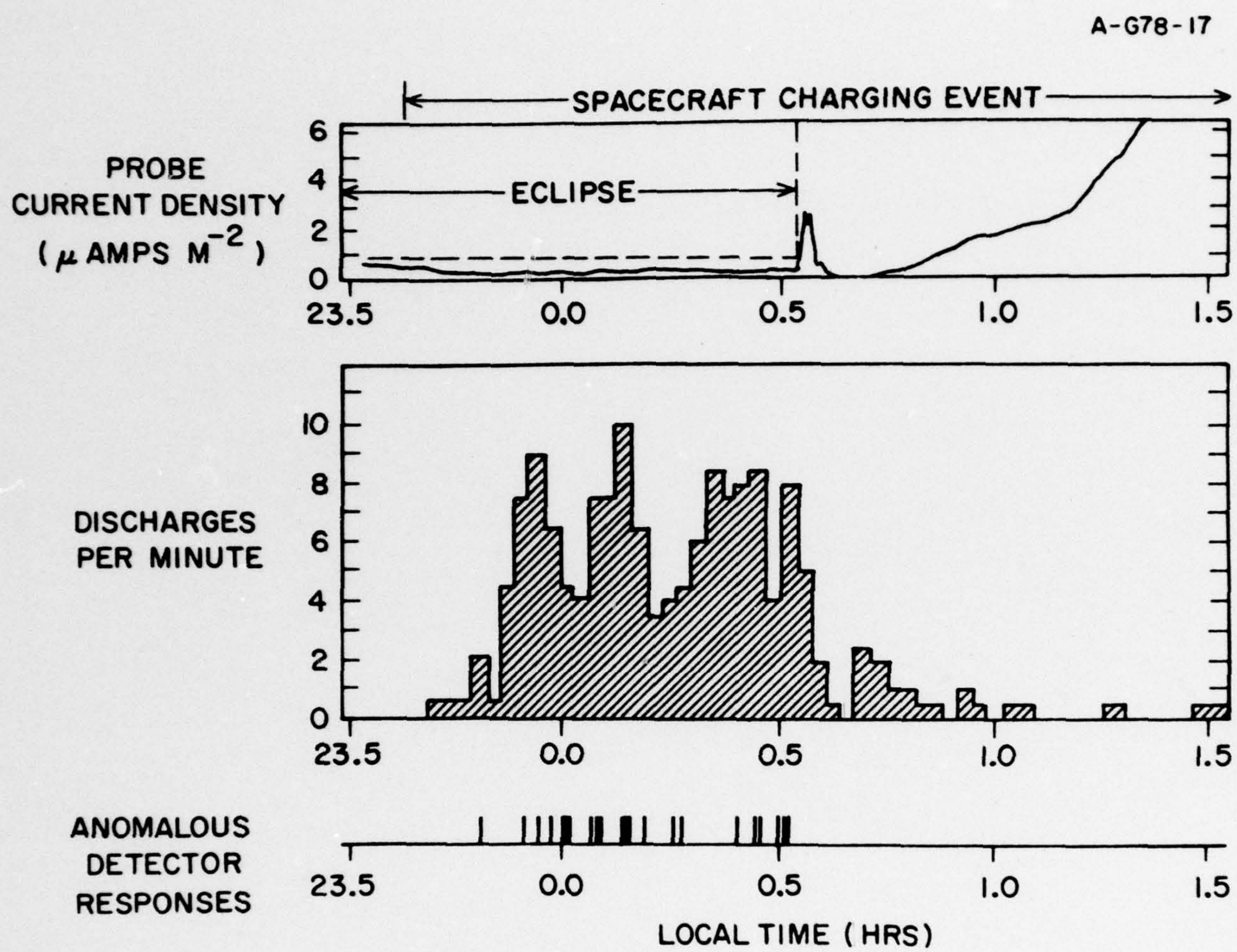
A-G78-17
SPACECRAFT CHARGING EVENT
PROBE
CURRENT DENSITY
(μ AMPS M^{-2})
ECLIPSE
6
4
2
0
23.5
0.0
0.5
1.0
1.5
DISCHARGES
PER MINUTE
10
8
6
4
2
0
ANOMALOUS
DETECTOR
RESPONSES
LOCAL TIME (HRS)

Figure 1

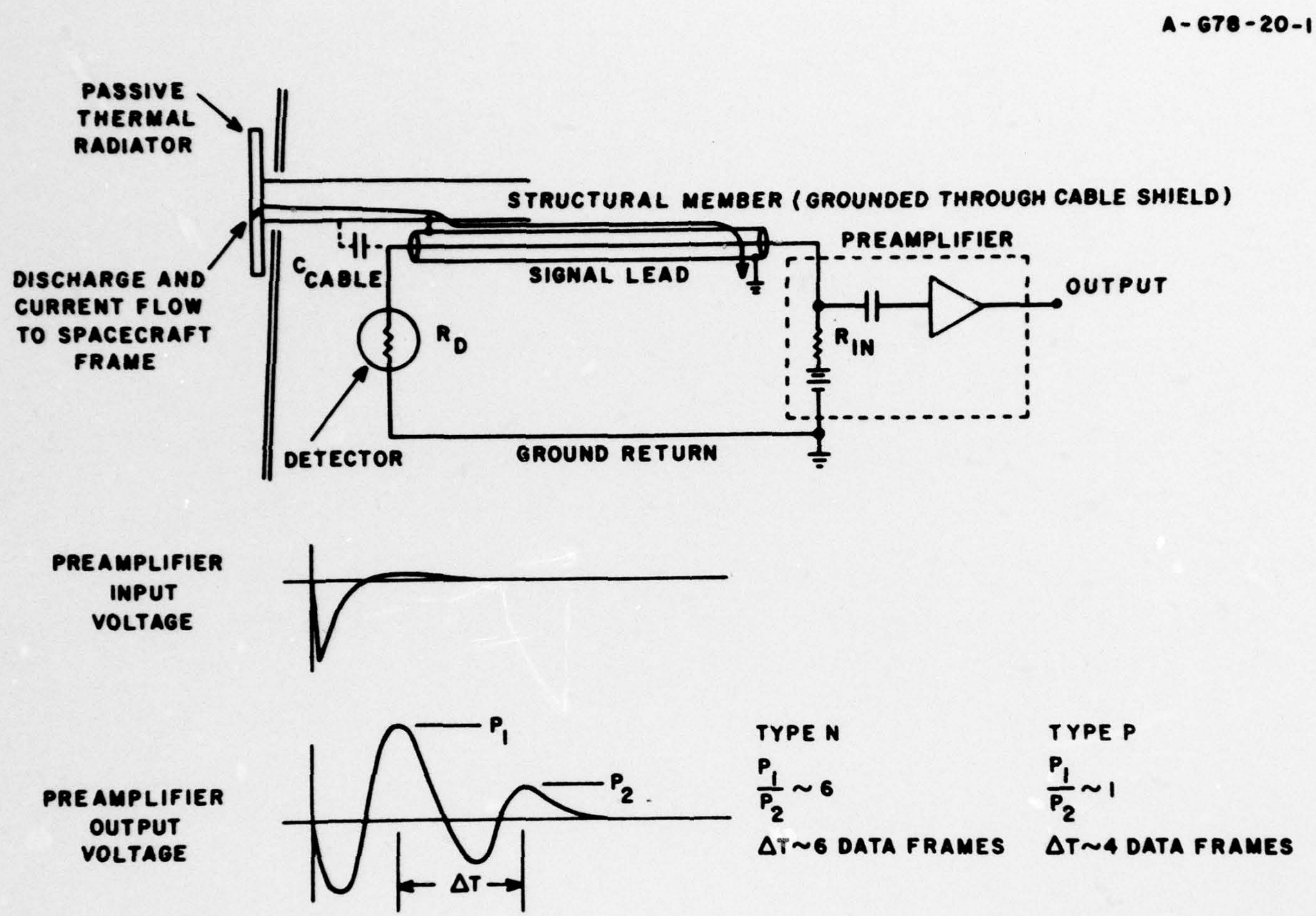
A-G78-20-1
PASSIVE THERMAL RADIATOR
DISCHARGE AND CURRENT FLOW TO SPACECRAFT FRAME
STRUCTURAL MEMBER (GROUNDED THROUGH CABLE SHIELD)
C_{CABLE}
SIGNAL LEAD
PREAMPLIFIER
OUTPUT
R_D
R_{IN}
DETECTOR
GROUND RETURN
PREAMPLIFIER INPUT VOLTAGE
PREAMPLIFIER OUTPUT VOLTAGE
P_1
P_2
ΔT
TYPE N
$\frac{P_1}{P_2} \sim 6$
$\Delta T \sim 6$ DATA FRAMES
TYPE P
$\frac{P_1}{P_2} \sim 1$
$\Delta T \sim 4$ DATA FRAMES

Figure 2

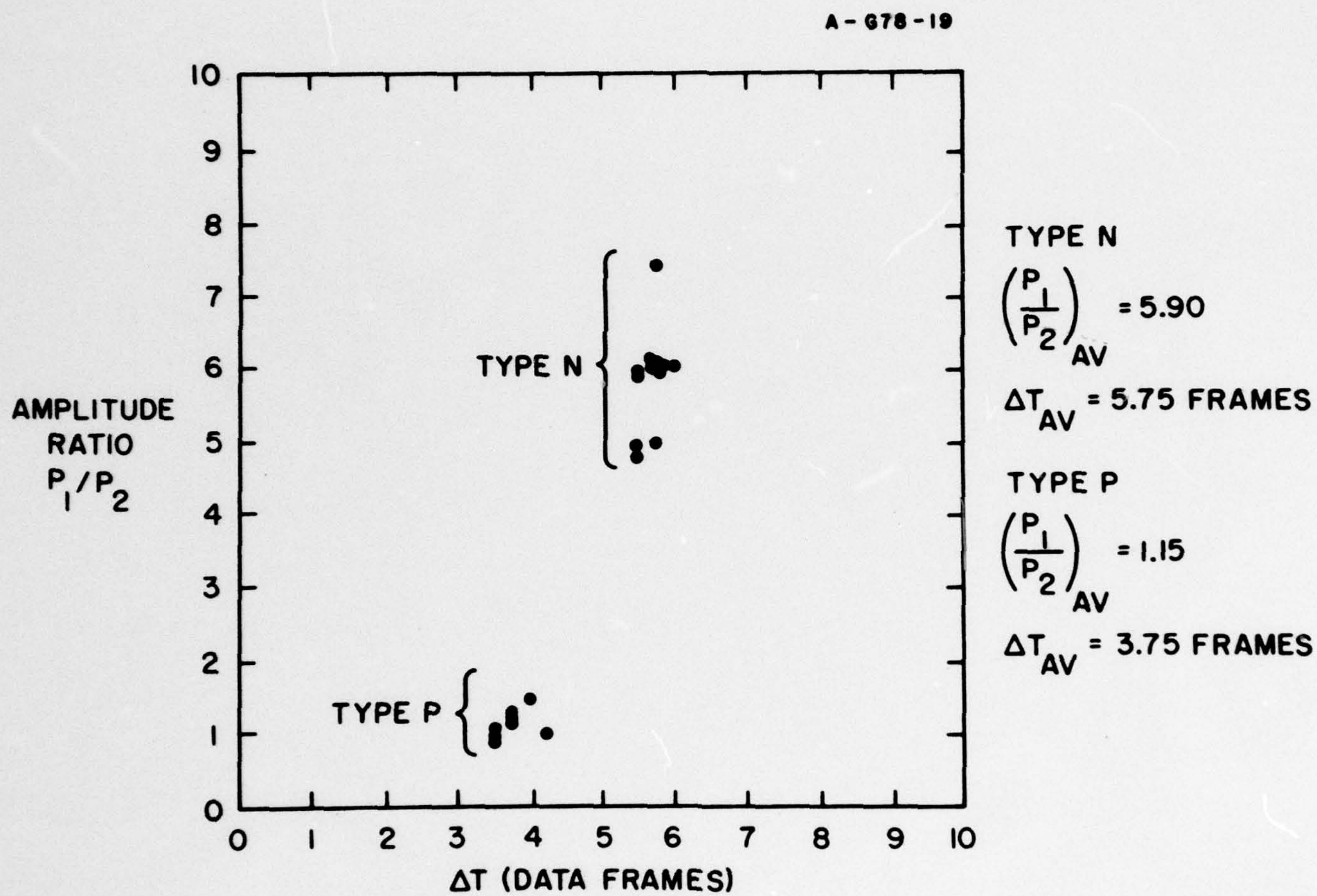
A-G78-19
AMPLITUDE RATIO P_1/P_2
TYPE N
TYPE P
ΔT (DATA FRAMES)
TYPE N
$\left(\frac{P_1}{P_2}\right)_{AV} = 5.90$
$\Delta T_{AV} = 5.75$ FRAMES
TYPE P
$\left(\frac{P_1}{P_2}\right)_{AV} = 1.15$
$\Delta T_{AV} = 3.75$ FRAMES

Figure 3

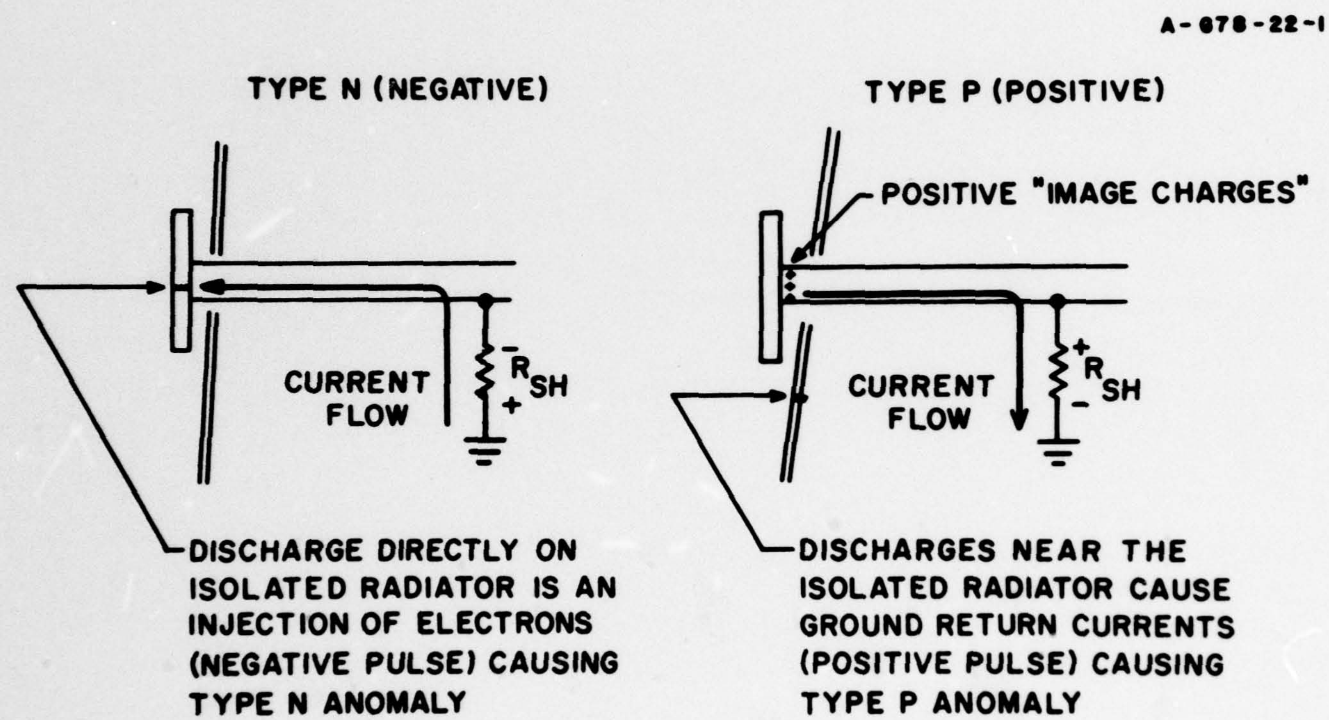
A-078-22-1
TYPE N (NEGATIVE)
TYPE P (POSITIVE)
POSITIVE "IMAGE CHARGES"
CURRENT FLOW
R_{SH}
CURRENT FLOW
R_{SH}
DISCHARGE DIRECTLY ON ISOLATED RADIATOR IS AN INJECTION OF ELECTRONS (NEGATIVE PULSE) CAUSING TYPE N ANOMALY
DISCHARGES NEAR THE ISOLATED RADIATOR CAUSE GROUND RETURN CURRENTS (POSITIVE PULSE) CAUSING TYPE P ANOMALY

Figure 4

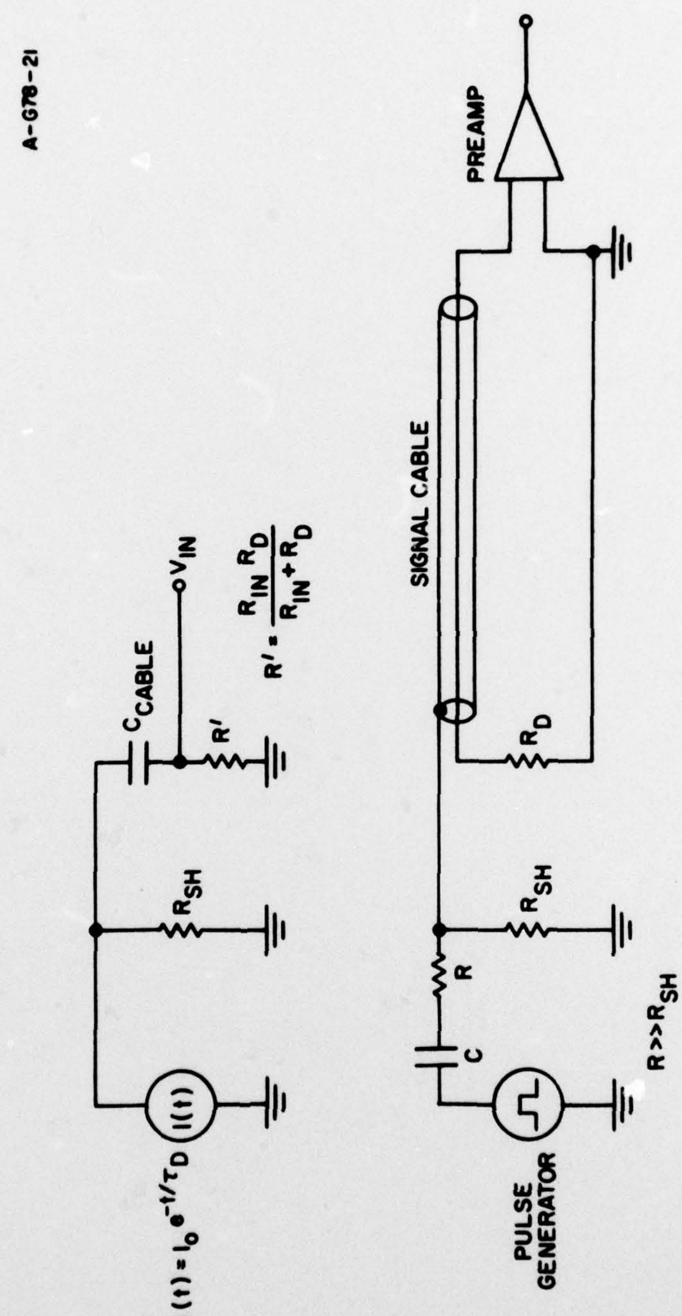
A-G78-21
$I(t) = I_o e^{-t/\tau_D}$
$I(t)$
R_{SH}
C_{CABLE}
R'
V_{IN}
$R' = \frac{R_{IN} R_D}{R_{IN} + R_D}$
PULSE GENERATOR
C
R
R_{SH}
$R >> R_{SH}$
R_D
SIGNAL CABLE
PREAMP

Figure 5

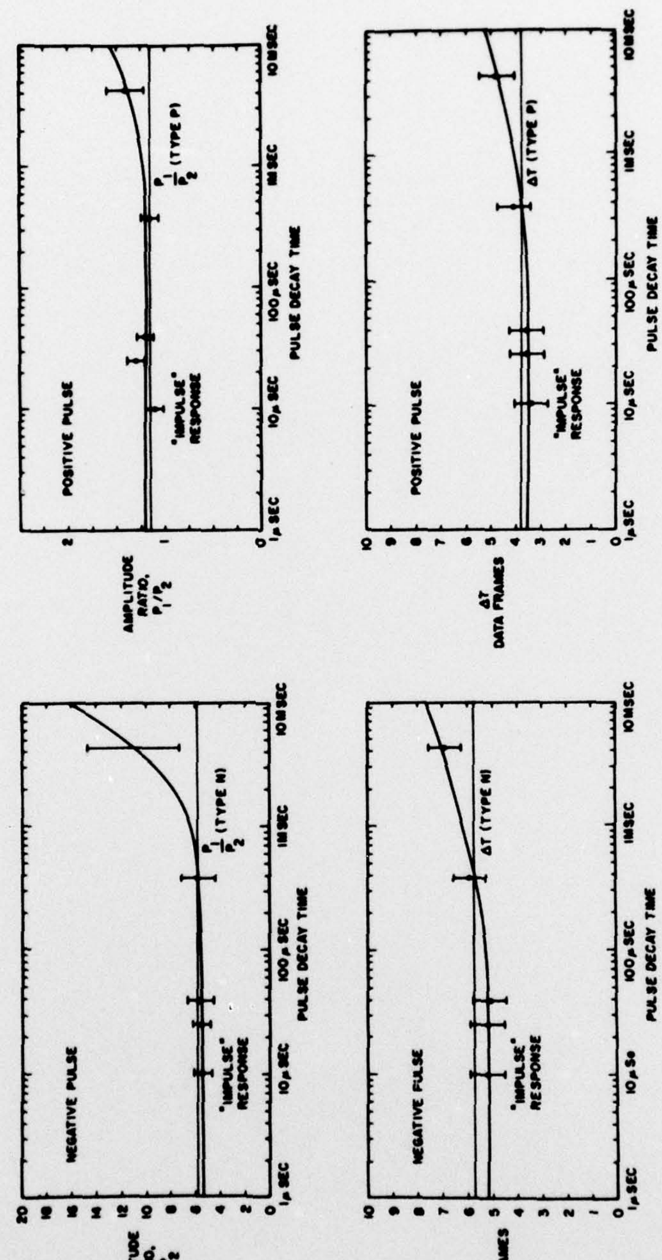
NEGATIVE PULSE
POSITIVE PULSE
AMPLITUDE RATIO, P_1/P_2
ΔT DATA FRAMES
"IMPULSE" RESPONSE
$\frac{P_1}{P_2}$ (TYPE N)
$\frac{P_1}{P_2}$ (TYPE P)
ΔT (TYPE N)
ΔT (TYPE P)
PULSE DECAY TIME
1μSEC
10μSEC
100μSEC
1MSEC
10MSEC

Figure 6